1 nterstellar Broadening of 1 mages in the Gravitational Lens PKS 1 8 3 0 - 2 1 1

1).1,. Jones, R. A. Preston, I). W. Murphy

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. 91109

1).1,. Jauncey, J. It. Reynolds, Al<. Tzioumis, E. A. King

Australia Telescope National Facility, CSIRO, Epping, NSW, Australia

1'. M. McCulloch, J .E. J. Lovell, M.E. Costa

Dept. of Physics, University of Tasmania, Hobart, Tasmania, Australia

and

'1'.1). Vail Ommen

Antarctic. CRC, University of Tasmania, Hobart, Tasmania, Australia

ABSTRACT

The remarkably strong radio gravitational lens PKS 1830-211 consists of a one arcsecond diameter Einstein ring with two bright compact (milliarcsecond) components located on opposite sides of the ring. We have obtained 22 GHz VLBA data on this source to determine the intrinsic angular sizes of the compact components. Previous VLBI observations at lower frequencies indicate that the brightness temperatures of these components are significantly lower than 10^{10} K (Jauncey, et al. 1991), less than is typical for compact synchrotron radio sources and less than is implied by flux density variations. A possible explanation is that interstellar scattering is broadening the apparent angular size of the source and thereby reducing the observed brightness temperature. Our VLBA data support this hypothesis. At 22 GHz the measured brightness temperature is at least [1]K and the deconvolved size of the core in the southwest compact component is proportional to ν^{-2} between 1.7 and 22 GHz.

Subject headings: galaxies: individual (PKS 1830-21 1) gravitational lensing — scattering

1. Introduction

The Einstein ring gravitational lens PKS 1830-211 is one of the strongest compact radio sources in the sky, nearly two orders of magnitude brighter at radio frequencies than any other known gravitational lens (Rao and Subrahmanyan 1988; Jauncey, et al. 1991). The source consists of a pair of bright compact (mas) components on opposite sides of a 1 arcsecond diameter ring of emission. Both compact components have been imaged with VLBI at 1.7 GHz (Jones, unpublished), 2.3 GHz (Jauncey, et al. 1991; King, et al. 1993), 5 GHz (Jones, et al. 1993; Jones 1994), and 22 GHz (Jones, et al. 1995 and this paper). Variations in the morphology of both compact components have been seen between two VLBI epochs at 5 GHz (Jones 1994). The extragalactic nature of PKS 1830-211 was confirmed by galactic HI emission and absorption measurements (Subrahmanyan, Kesteven, and te Lintel Hekkert 1992).

The large radio flux density of PKS 1830-211 has allowed a large quantity of high signal-to-noise single-dish and interferometric data to be obtained (e.g., Subrahmanyan, et al. 1990; Jauncey, et al. 1992, 1993; van Ommen, et al. 1995; Lovell, et al. 1995). This wealth of observational information provides strong constraints on the geometry of the lens system and may lead to an accurate estimate of the large-scale value of H_0 when combined with redshifts and the differential time delay between the two images.

The over-all morphology of the source has been successfully modeled as a background core-jet radio source lensed by a single medium-mass galaxy (Kochanek and Narayan 1992; Nair, Narasimha, and Rao 1993). Optical redshifts are still unavailable because the position of PKS 1830-211 is close to the galactic center ($l = 12.2, b = -5.7$) in a region crowded with foreground stars (Djorgovsky, et al. 1992; Jauncey, et al. 1993). However, the redshift of the lensing galaxy has been recently determined from radio absorption line observations (Wiklind and Combes 1996). The time delay between the two compact

components has been estimated as 44 ± 9 days by van Ommen, et al. (1995) based on multi-epoch V A images. Proposed observations with the VSOP spacecraft could i mprove the of the time delay determination

One of the aspects of this source which has been difficult to explain is the unusually low brightness temperatures of the two compact components. The total flux density varies by factors o more than 2 on time scales of months and years (lovell, et al 995, which i uplies a smaller angular size and higher brightness temperature than seen in VLBI images at frequencies ≤ 5 GI z. Since the line of sight to PKS 830-2 passes close to the galactic center, it is plausible that significant nterstellar scattering (ISS within our galaxy may occur along this line o sight Scattering by the interstellar medium in the lensing galaxy will be far less significan than ISS withi our galaxy (Walker 1996) The effects of SS decrease rapidly with frequency, and should be significantly smaller at 22 GHz.

2. Observations

We observed PKS 8 22 with the full VLBA at 22 GHz in May 1994. The data were correlated in Socorro twice using phase centers corresponding to the locations o the two compact components, which we designate the northeast (NE) and southwest SW) components. The observations were inadvertently made in dual-polarization mode, which resulted in much less suppression the component far from the phase center (by decorrelation over the observing bandwidth) than expected As a result, it was necessary to include both compact components in the imaging process. After manual phase calibration, amplitude calibration, and fringe fitting in AIPS¹ we used the Caltech program

The Astronomical nage Processing System was developed y the National Radio Astronomy Observatory, which is operated by Associated iversities, nc., under a

Difmap (Shepherd, Pearson, and Taylor 1 **994**) for editing, self-[:alil)latic)ll, imaging, and deconvolution. The data were coherently averaged to 15 seconds, and the errors were estimated from the scatter of the 1-second data points within each averaging interval.

Phase-only corrections were applied during each "selfca - invert-clean" cycle until the model flux density matched that of the visibility data on the shortest baselines to within a few p ercent. At that point time-independent antenna gain corrections were allowed (these corrections were $\leq$ 12% for all antennas) for several cycles, followed by time-dependent gain corrections with decreasing time scales until full point-by-point amplitude self-calibration was applied. The self-cal solutions remained very stable from one cycle to the next. The final agreement factor (reduced χ^2) between our model and the self-calibration data was 0.86.

3. Results

Figures 1 and 2 show our VLBA images of the NE and SW components of PKS 1830-211, respectively. The NE component appears to have a jet extending at least 12 mas **towards** the NW, and a bright core that is slightly extended towards the NW as well. The SW component appears to be very nearly unresolved. Recent 15 GHz VLBI observations by Garrett, et al. (1995) confirm that the NE component has a well-defi**cd jet as well as a core, while the SW component is essentially unresolved (see also Patnaik and Porcas 1995). The SW component in PKS 1830-211 is the more compact of the two bright components at all frequencies, and consequently is the best one to use as a test for ISS broadening. The 22-GHz image of the SW component shown in Jones, et al. (1995) has slightly higher angular resolution but significantly lower dynamic range than the image in figure 2.

EDITOR: PLACE FIGURE 1 HERE.

EDITOR: PLACE FIGURE '2 HERE.

The angular separation between the brightest peaks in figures 1 and 2 is 972 ± 1 mas. VLBI observations of PKS 1830-21] at 5 GHz in November 1990 and September 1991 indicated angular separations of 975 ±2 and **973** ±2 mas, respectively (Jones, et al. 1993). Thus, we find no evidence for a significant change in separation over 3.5 years. As Williams and Saha (1995) point out, centroid shifts causal by microlensing should not be detectable in radio images.

Figure 3 show the deconvolved minor axis width of the SW component at four frequencies: 1.7 GHz (unpublished data from an ad-hoc VLBA experiment in 1990), '2.3 GHz (King 1995), 4.9 GHz (Jones 1994), and 22 GHz (this paper). Deconvolved sizes are used to remove (or at least reduce) the bias in observed angular sizes which is introduced by the limited range of baseline lengths in each VLBI array. We compare the minor axis sizes because intrinsic source structure is more likely to contribute to the major axis size. The slope of the line fit to the angular size measurements in figure 3 is 1.92 ± 0.14, consistent with the λ^2 dependence expected for scattering. This suggests that **angular size** measurements made by VLBI at frequencies $\leq$ 22 GHz are indeed affected by angular broadening due to 1SS.

EDITOR: PLACE FIGURE 3 HERE.

At **22** GHz the deconvolved size of the SW component core is less than 0.6 x **0.2** mas and $T_b \geq 10^{11}$ K. This is much more typical of the brightness temperatures seen in other extragalactic compact radio sources.

4. Discussion

The amount of ISS expected for a line of sight passing close to the center of our galaxy can be estimated from the measured angular broadening of isolated H_2O maser features in W49(N) and Sgr B2. Gwinn, Moran, and Reid (1988) found minimum angular sizes of 0.2 mas in W49 and 0.3 mas in Sgr B2. This is consistent with our measured angular size of the SW component core in PKS 1830-211 at 22 GHz. Gwinn, Moran, and Reid also found that 0 1 1 masers in W49 and Sgr B2 had angular sizes consistent with $\Theta \propto \lambda^2$ when compared with 1 1 0 maser sizes in those objects.

It is interesting to compare our measurements with those predicted by the Blandford and Narayan (1985) formula for ISS:

$$\Theta_{ISS} \sim 2(C_n^2)^{3/5} \lambda^{11/5} D^{3/5} \text{ arcseconds,}$$

where λ is the wavelength in meters and D is the path length through the ISM in kpc. C_n^2 gives the strength of electron density fluctuations in the ISM. Anantharamaiah and Narayan (1988) find $C_n^2 \approx 1.5$ for low galactic latitudes and $|l| \leq 30°$; we use a value of 1 since the galactic latitude of PKS 1830-211 (- 5°.7) is not very small. Setting $\lambda = 0.013$ meters and $D \approx 5$ kpc (the path length for $|b| = 5°.7$ through a plane parallel ISM with a height of 500 pc) gives us $\Theta_{ISS} \approx 0.4$ mas. This is also consistent with our angular size determination for PKS 1830-211.

Future work may allow this analysis to be extended to the core of the NE component. This will be more difficult because of the higher level of extended emission associated with the NE component, particularly very close to the brightest peak. If we can determine the degree of angular broadening of the NE component core due to ISS we will have an opportunity to study differences in the scattering properties of our galaxy's ISM at multiple frequencies along two lines of sight one arcsecond apart. The results presented here also

suggest that still higher frequency VLBI observations of PKS 1830-21 1 will be useful, since the intrinsic angular size of the radio source core is still not causing a significant deviation from the $\theta \propto \lambda^2$ relation at 22 GHz.

REFERENCES

Anantharamaiah, K.R. and Narayan, R. 1988 in Radio Wave Scattering in the Interstellar Medium, ed. J. Cordes, B. Rickett, and D. Backer (AIP: New York), 185

Blandford, R. and Narayan, R. 1985, MNRAS, 213, 591

Djorgovski, S., Meylan, G., Klemola, A., ']']10111])S011, D. J., Weir, W. N., Swarup, C., Rao, A.]'., Subrahmanyan, R., and Smette, A. 1992, MNRAS, 257, 240

Garrett, M. A., Nair, S., Porcas, R.W., and Patnaik, A.R. 1995, in Astrophysical Applications of Grav. Lensing, ed. C. Kochanek and J. Hewitt (Kluwer), 189

Gwinn, C.R., Moran, J.M., and Reid, M. J. 1988, in Radio Wave Scattering in the Interstellar Medium, ed. J. Codes, B. Rickett, and D. Backer (AIP: New York), 129

Jauncey, D. JJ., et al. 1991, Nature, 352, 132

Jauncey, D.L., et al. 1992, in Gravitational Lenses, ed. R. Kayser, T. Schramm, and L. Nieser (Springer Verlag: Berlin), 333

Jauncey, D.L., et al. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis and R. Booth (Cambridge: Cambridge Univ. Press), 134

Jones, D.L., et al. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis and R. Booth (Cambridge: Cambridge Univ. Press), 150

Jones, D.L. 1994, in Compact Radio Sources, ed. J.A. Zensus and K.I. Kellermann (Socorro: NRAO), 135

Jones, D.L., Preston, R.A., Murphy, D. W., Meier, D.L., Jauncey, D.L., Reynolds, J.E., and Tzioumis, A.]{. 1995, in Astrophysical Applications of Gravitational Lensing, ed. C. Kochanek and J. Hewitt (Kluwer), 345

King, E.A., et al. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis and R. Booth (Cambridge: Cambridge Univ. Press), 152

King, E. A. 1995, Ph.D. Thesis, Univ. of Tasmania

Kochanck, C. S. and Narayan, R. 1992, ApJ, 401, 461

Lovell, J.E. J., McCulloch, P. M., King, E.A., and Jauncey, D.L. 1995, in Astrophysical Applications of Grav. Lensing, ed. C. Kochanck and J. Hewitt (Kluwer), 347

Nair, S., Narasimha, D., and Rao, P. 1993, ApJ, 407, 46

Patnaik, A.R. and Porcas, R. W. 1995, in Astrophysical Applications of Gravitational Lensing, ed. C. Kochanck and J. Hewitt (Kluwer), 305

Rao, A.P. and Subrahmanyan, R. 1988, MNRAS, 231, 229

Shepherd, M. C., Pearson, T.J., and Taylor, G.B. 1994, BAAS, 26, 987

Subrahmanyan, R., Narasimha, D., Rao, A.P., and Swarup, G. 1990, MNRAS, 246, 263

Subrahmanyan, R., Kesteven, M.J., and te Lintel Hekkert, P. 1992, MNRAS, 259, 63

van Ommen, T.D., Jones, D.L., Preston, R. A., and Jauncey, D.L. 1995, ApJ, 444, 561

Walker, h4. 1996, in Extragalactic Radio Sources (Kluwer), in press.

Wiklind, T. and Combes, F. 1996, Nature, 379, 139

Williams, L.L.R. and Saha, P. 1995, AJ, 110, 1471

Fig. 1. VLBA image of the NE compact component in PКS 1830-211 at 22 GHz. The contours are -1, 1, 2, 4, 8, 16, 32, 50, **70,** and 95%, and the restoring beam (shown in the bottom left corner) is an elliptical Gaussian with FWHM of 2.2 X 1.1 mas and the major axis along position angle 1.5°. The absolute flux density scale is not well calibrated, but this changes only the peak brightness level of the image and not the morphology of the source.

Fig. 2. VLBA image of the SW compact component in PKS 1830-211 at 22 GHz. The contours are -0.5, 0.5, 1, 2, 4, 8, 16, 32, 50, 70, and 95%, and the restoring beam is the same as in figure 1

Fig. 3. The deconvolved minor axis angular size of the SW component core at 22 GHz (λ = **1.3** cm), 5 GHz (λ = **6** cm), 2.3 GHz (λ = 13 cm), and 1.7 GHz (λ = 18 cm). The deconvolved sizes and their (formal) errors at **22, 5,** and **1.7** GHz were determined with the AIPS program IMFIT, using only the upper 50% of the brightness range to avoid bias by any extended low-level structure. The size at 2.3 GHz is taken from King (1 995). A least-squares linear fit to the data points is shown: this line has a slope of 1.924 0.14.

Relative R.A. (milliarcsec)

Relative Decl. (milliarcsec)

Relative R.A. (milliarcsec)

Relative Decl. (milliarcsec)

Log (size in mas)

Log (wave ength in cm)